

Michigan State University
ECE 480 - Spring 2015
Team 10 – Tool Condition Monitoring System
Final Report



Caitlin Slicker
Richard Skrbina
Ali ElSeddik
Chris Vogler
Kyle Burgess

May 1st 2015

Executive Summary:

Great Lakes Controls & Engineering has identified the problem of monitoring tool wear in a multi-spindle automatic screw machine. It is necessary to monitor the wear of a cutting tool so as it becomes dull, it can be replaced before producing faulty parts.

Team 10 implemented a solution using an accelerometer to measure the subtle vibrations caused by the machining process, which change with tool life. The team built an embedded system which analyzes both the frequency and amplitude of the accelerometer's output. The system was calibrated based on data gathered by the team on a single spindle lathe; however, the device can be adapted for a number of machines and purposes.

Acknowledgements:

Design Team 10 would like to thank Justin Walz of Great Lakes Controls Engineering for sponsoring our project and allowing us to test at their machine shop facility, Maes Tool in Jackson, MI. We would like to thank the employees of Maes Tool for operating the lathe, allowing us to take data, and providing valuable insight into the project requirements. We would like to thank Brian Wright, Gregg Mudler, and Roxxane Peacock of the ECE Shop for supplying electronic components and allowing us to loan lab equipment for gathering data in various machine shops. We would also like to thank Dr. Joydeep Mitra for being our facilitator and keeping us on track during this semester. Finally, we would like to thank Dr. Timothy Grotjohn, Dr. Lalita Udpa, and the many guest speakers in class for their inspiration and encouragement.

Table of Contents

1. Chapter 1: Introduction and Background.....	4
1. Project Description.....	4
2. Current Commercial Systems	5
3. Overview of Tool Wear	5
2. Chapter 2: Exploring the Solution Space.....	7
1. Sensor Options.....	7
2. Analysis and Design Decision	12
3. Schedule and Project Planning.....	15
4. Project Budget.....	17
3. Chapter 3: Technical Description	18
1. Power Supplies.....	18
2. Sensor Interface Circuit	18
3. PWM and Filters	19
4. Comparator and Interrupt.....	19
5. Adjustable Band Pass Filter	20
6. Prototype Implementation.....	22
4. Chapter 4: Testing and Validation	23
1. Testing Plan and Data	23
2. Final Outcomes	29
5. Chapter 5: Final Cost, Schedule, Summary, and Conclusions	31
6. Appendix 1: Technical Roles.....	33
7. Appendix 2: Literature Review	38
8. Appendix 3: Detailed Technical Attachments	41

Chapter 1: Introduction and Background

1.1 Project Description

The purpose of this project is to detect the wear of a cutting tool used in multi-spindle automatic screw machine. A screw machine is a metal-working machine “that continuously creates a number of finished parts from bar stock. Bar stock advances through the spindle and is held by a collet. It is also commonly called a bar machine. The cutting tool is gradually passed along the surface of the rotating part.” [1].

As a cutting tool becomes dull, faulty parts are produced. Figure 1.1 shows a part that has been manufactured using a dull cutting tool where the radial imperfections could be visibly seen. Currently, the factory that produces these parts depends on a part-production counter to determine when to change a cutting tool. The cutting operation is done using what they refer to as a ‘box’ cutting tool. After 40,000 aluminum parts are produced using the box tool, the cutting tool is changed. However, because of variations in materials, humidity, temperature, or even lubricant viscosity, the number of parts a given cutting tool can produce varies from this set number. As a result, it is desirable to have a system that can dynamically detect a dull cutting tool and indicate to the machine operator to replace the tool.



Figure 1.1: Faulty Production Part

Great Lakes Controls and Engineering detailed a number of specifications that the team’s system must meet. First, the system must detect the wear on only one cutting tool in real time, rejecting the noise produced from the simultaneous machining operations of the other five cutting tools. The system needs to produce an output signal to the Programmable Logic Controller (PLC), viewable by the machine operator, which indicates the current level of tool life remaining. This output must be a 0-10 V signal mapping of the percent tool life remaining. Because the system is an extension of the PLC, it must run off the same 24 V power supply. Additionally, the entire product must not be larger than 2” x 2” x 2” in order to fit within the machine without disrupting normal operation. The budget for volume production must not be greater than \$250.

In addition to these basic qualifications, the system ought to auto-calibrate in the case of a tool being replaced. In other words, when a machine operator receives the signal to replace the lathe tool and does so, the system's output to the PLC should automatically reflect this change without needing to be reset or any other calibration. Furthermore, the environment within the machine is very volatile where coolant and metal shavings are constantly being projected during machining operation, and so the device must be able to withstand this environment.

1.2 Current Commercial Systems

Given that most screw machines were built over fifty years ago, there is an increasing interest within the industry to develop systems that can detect tool life for machining processes. Whether it is to identify how much longer a tool can be run until product imperfections occur or the precise moment a tool fails, there are effective solutions to measure both. There are a number of sensor and sensing systems specifically designed to accommodate most machines and machining processes. Commercial systems include those from companies such as Nordmann, Montronix, and Prometec. These companies provide a variety of solutions for monitoring different parameters of tool condition including force monitoring, electric power consumption, and acoustic emission sensing, but for a significantly expensive price. For a variety of reasons, most of these systems could not be directly implemented to the customer's machine. The team took inspiration and technical consultancy from these companies to produce a system adaptable to the customer's machine. Figure 1.2 illustrates a Normann developed system for monitoring tool breakage on a six-spindle automatic lathe [2].

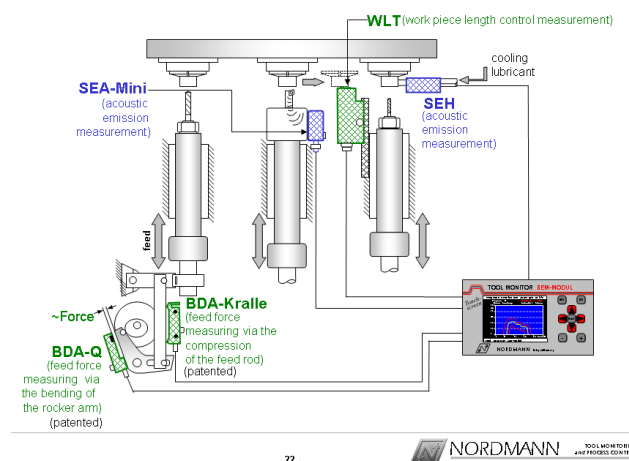


Figure 1.2: Normann Tool Condition Monitoring System

1.3 Overview of Tool Wear

It is necessary to first understand and quantitatively define what tool wear is. Tool life, according to Mikell P. Groover's Fundamentals of Modern Manufacturing, "is defined as the length of cutting time that the tool can be used. Operating the tool until final catastrophic failure is one

way of defining tool life” [3]. Groover further explains that a tool can fail from three different causes: fracture failure, temperature failure, and gradual wear. Fracture failure and temperature failures are when a cutting tool breaks due to excessive force or high temperatures on the tool. On the other hand, gradual wear can either be crater wear which is caused by the action of the chip as it is being removed from the work surface or flank wear which results from the rubbing between the newly generated work surface and the flank face of the cutting tool [4]. Gradual flank wear is the focus of the project. Flank wear can be approximated using tool life according to the Taylor tool life equation where:

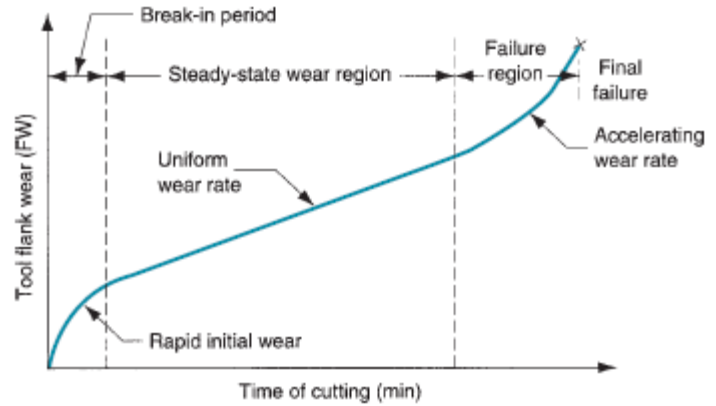


Figure 1.3: Taylor Tool Life Equation [3]

where: v : spindle cutting speed, T : tool life

n and C depend on feed, depth of cut, work material, tooling, and the tool life criterion used.

Figure 1-3 plots the cutting tool's wear as a function of time according to Groover's Fundamentals of Modern Manufacturing [3]. Three regions could be seen where the tool wear increases rapidly over the initial 'break-in' period, then linearly in the 'steady-state' wear region and finally the cutting tool is prone to failure within the final 'failure' region.

The Taylor tool life equation is only a theoretical measure of a cutting tool's tool life within the specified parameters that are determined by prior experimentation or known published research data. It doesn't directly apply to the project's development; rather, it gives the team a measure on the effects of speed and feed rate on the operation. These relationships became vital later in the progress of the project when testing the device at different cutting speeds.

Chapter 2: Exploring the Solution Space

2.1 Sensor Options

When producing a system that would monitor the tool wear of an automated lathe, the most critical component was the sensor. At the onset of this project, the team conducted extensive research to determine what method of sensing would most effectively achieve the overall goal. Some of the parameters taken into consideration included the sensor price, frequency range, and feasibility. The following methods were put into a feasibility matrix before a final selection was made.

Audio: To an experienced machine operator, there is a distinguishable audible difference between new and used cutting tools. A tool in poor condition emits a higher amplitude and frequency output during cutting. For this reason, this was the suggested method of tool wear sensing by Great Lakes Controls & Engineering.

To meet the requirement of sensing a single tool on the six spindle lathe, the sensing device must be placed 2 feet away from the lathe and should only listen to an area of 4 square inches. To achieve this design specification, the angle of incidence must be 4.76° . To understand how this might be accomplished, the polar patterns of microphones must be taken into consideration. A polar pattern is coordinate plane where the sensitivity of a microphone can be plotted relative to the angle of incidence that the sound hits [5]. Figure 2.1 shows the five common polar patterns of microphones. In comparison, the 4.76° angle of incidence sensitivity is shown in Figure 2.2.

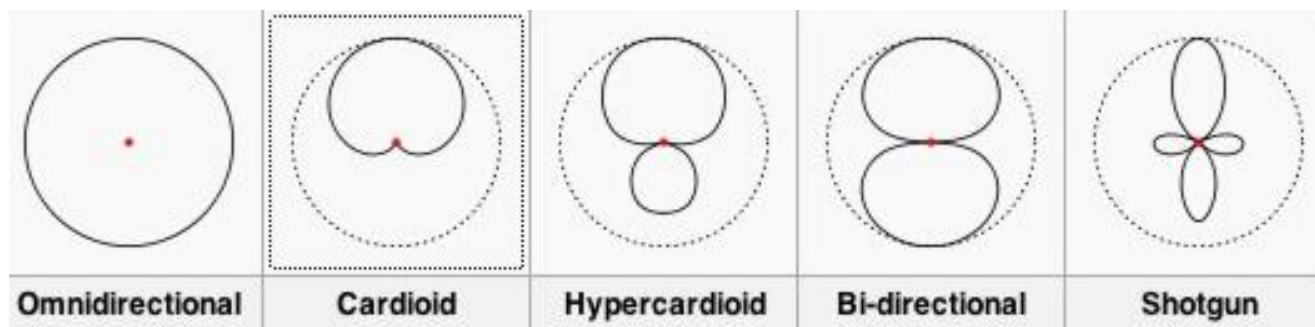


Figure 2.1: Common Polar Patterns of Audio Microphones

It was determined that a purely audio solution would not be possible for several reasons. First, by analyzing the polar patterns of most commercial microphones, a single microphone

would not be able to capture the sound of a single tool with necessary accuracy. A shotgun microphone has the narrowest polar pattern but it is still much wider than the 4.76° angle of incidence sensitivity needed [6]. Additionally, the size of a shotgun type microphone greatly exceeded the size requirements for this project. Directionality could be increased with an array of microphones, also known as beamforming, but because of the highly resonant enclosure of the lathe, standing and reflected waves eliminate the ability to filter out noise in an audio recording [6] [7] [8]. The team also considered more exotic acoustic solutions such as laser vibrometry and ultrasound but these were determined to be prohibitively expensive and not well suited to the environment within the lathe [9].

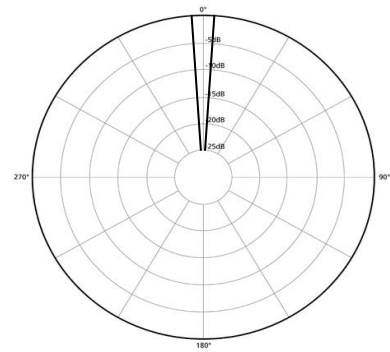


Figure 2.2: Approximate Representation of 4.76° Polar Pattern

Acoustic Emissions: Acoustic Emission (AE) is the phenomenon that under stress or pressure, materials rapidly emit energy in the form of transient elastic waves [10]. When irreversible deformation occurs, these vibrational waves can be measured to determine structural properties of the material of interest. Because these high frequency waves typically range from 100 kHz to 1 MHz, AE sensors are primarily designed based on frequency and desired bandwidth [11].

For tool monitoring, there are three methods in which AE sensors can be used. The first type of AE sensor uses a cooling or lubricant jet as a waveguide, that is, a method of wave transmission. The sensor is placed directly on a line directed at the cutting operation, and the emitted waves travel through the liquid back to the sensor. The second type of AE sensor is placed directly on the tool close to the cutting operation, thus the waves are transmitted directly through the tool material itself. The third type simply uses air as a medium of transmission to capture the radiation of acoustic waves when the sensor is placed in close proximity to the operation. The Figures below are examples of these types of acoustic emission sensors [12].

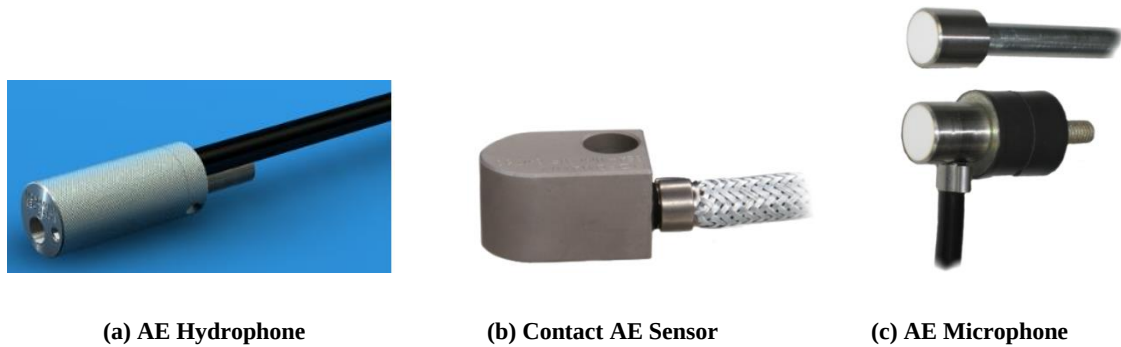


Figure 2.3: Types of Acoustic Emission Sensors [16]

It was initially thought that acoustic emission testing would be the appropriate choice for real-time tool monitoring. However, after consulting with an expert in the field of AE sensors for tool monitoring, it was discovered that AE sensing is particularly useful in detecting tool breakages, where short, high-amplitude spikes from fracturing can be detected quickly. However, measuring wear over the course of a tool's life would not be effectively achieved through this method. Another drawback was the lack of quantitative data regarding the emitted frequencies from the tool under different loads. It was known through research that the frequencies detected using acoustic emissions sensors would exceed the human audible spectrum (20 kHz) and could drift into the MHz range. Frequencies that high could present hardware and processing issues, while choosing a sensor with the wrong frequency range could render meaningless data. Finally, after obtaining several quotes for AE sensors, it was determined that this method would also be outside the team's budget.

Power Consumption: When a tool is sharp, it cuts through metal easily. As it dulls, there is greater mechanical resistance as the tool begins to drag across the part. The machine must now work harder to maintain the same RPM, which causes an increase in power consumption. The life of a tool can thus be measured accurately by analyzing the power consumption during operation. This can be applied to a wide variety of machines such as CNC mills and lathes, machining centers and transfer lines, and grinding applications. The sensor itself works based on the Hall Effect, which states that a current carrying conductor in a magnetic field will generate a voltage proportional to the current and magnetic field [13]. The sensor measures this voltage difference, called the Hall voltage, which is used to calculate the instantaneous power to the load.

Monitoring by power consumption provides accurate measurements and is especially effective in detecting tool breakages. Because sensing components use the Hall Effect, the sensor responds to magnetic fields and are therefore easy to install because they do not require power lines to be modified or disrupted. This provides a non-intrusive system that does not interfere with the cutting operation.



Figure 2.4: 3-Phase Effective Power Measurement Unit [2]

Nonetheless, power sensors are not well suited to all applications. Small cutting or drilling tools are difficult to measure because there might be very little fluctuation in the power consumption from a good to poor tool. Also, operations that involve common-drive spindles, such as a six-spindle lathe, cannot use power consumption as a technique [12].

In the case of the six-spindle automatic lathe being used in this project, all six spindles are driven by a single power supply. As a result, variations in power consumption that resulted from any single tool would be indistinguishable from the overall power consumption of the machine or the wear of other tools. While this would have been an ideal solution, the team immediately ruled out this method from the selection matrix.

Force Sensing: Cutting tools are designed to remove material from an object based on the amount of force applied, as shown in Figure 2.5. This applied force increases as a tool wears out and becomes dull. The rate at which this force increases is heavily based upon the materials being machined as well as the tooling material. Therefore, the remaining tool life can be determined by the increased force applied by a cutting tool [12].

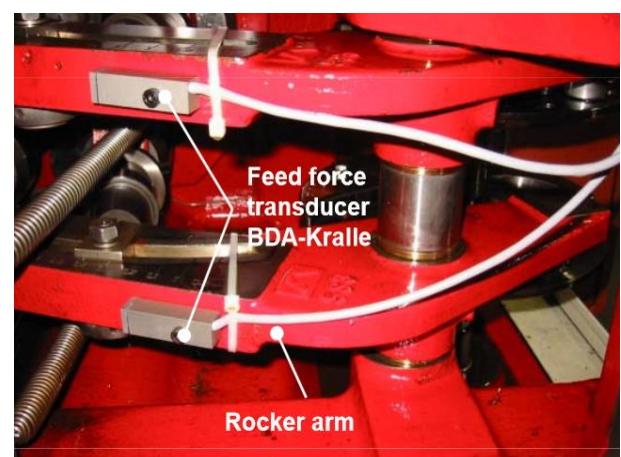


Figure 2.5: Force Sensor Placement on Rocker Arm [22]

In a multi-spindle lathe, there are two applications in which force sensing can be applied and interpreted. These methods utilize a strain gauge sensor placed on the rocker arm or the feed rod, which controls the tool performing the cutting. These highly sensitive gauges can detect micro or nanometer fluctuations in the tool position. The strain put on the feeding system while this cutting process occurs is measured and as it increases over time, it can thus be translated to a decrease in tool life. Alternatively, the gauge can also capture data regarding the moment the cutting tool makes contact with the material to be machined. By monitoring the transient response at the start of the cutting operation, it can be shown that there will be a difference in the tool movement when a sharp tool is used versus a deteriorated tool. The force needed to start the initial cut of material will increase and there will be more fluctuations in tool position as initial contact is made between tool and part [12].

While this solution seemed to be acceptable at first, it was not cost effective. Strain sensors designed for this application were not available to stay within the team budget. Ultimately force sensing was ruled out for this reason.

Accelerometer: An accelerometer is a device which measures g-force, or the force of gravity. It will measure 9.81m/s^2 while stationary and zero while in free-fall. The output is a continuous voltage that is proportional to the g-force experienced by the accelerometer. For example, the sensitivity of accelerometers can be denoted as 50 mV/g or 100 mV/g. Accelerometers can use piezoelectric (internal crystals respond to stress), piezoresistive (resistance changes based on force applied), or piezocapacitive (capacitance between microstructures changes based on accelerative force applied) principles to measure changes in acceleration [14]. An accelerometer can be an inexpensive, general-purpose solution to measuring internal vibrations within a solid. The frequencies measured are typically lower, from 10 Hz to 30 kHz. Accelerometers are not inaccurate; rather they are most effective for large-scale operations.

In relation to tool monitoring, there are two design solutions in which an accelerometer can be used. The first design measures the vibration of the tool as it is in use. The accelerometer would be mounted as close as possible to the cutting operation. The accelerometer is a pure transducer, meaning the output is a voltage with a frequency equivalent to the vibrations produced by the cutting operation. This data would be recorded for both good and poor condition

tools, and the harmonic frequency differences could create criteria in which to compare future tools. The second design solution is concerned with the transient response of the tool as it makes initial contact with the part being machined. Similar to force measurements, these vibrations should intensify as the tool becomes dull, because there is an increased resistance. Therefore, when initial contact occurs, a good tool will begin removing material quickly while a poor tool will experience a larger “bounce back” effect before cutting, resulting in increased vibrations.

Sensor Selection: Many sensing options were available for the monitoring of tool wear. However, these options were either not applicable to the specific process or machine specified by Great Lakes Controls and Engineering, or were beyond the allotted budget. Based on the team’s understanding of commercial tool monitoring sensors, it was decided that a general purpose accelerometer would measure similar metrics related to tool wear as other commercial options, but at a lower cost. As discussed earlier, the team used the design selection matrix shown below in Table 2.1 to rank each sensor by criteria. While not being the top solution, an accelerometer offered simplicity, affordability, and an overall lower risk than other sensors.

Engineering Criteria	Importance	Possible Solutions					
		Force	Accelerometer	AE	Coolant	Microphone	Power
Sensitivity to Noise	3	9	3	3	3	1	9
Installation	2	3	3	3	1	3	9
Durability	1	9	9	9	3	3	9
Data Correlation to Tool Life	5	9	3	5	3	1	3
Output Compatibility	4	3	3	3	3	3	9
Price	2	1	9	1	1	3	1
Total		101	78	63	43	35	107

Table 2.1: Solutions Selection Matrix for Tool Monitoring Sensors

2.2 Analysis and Design Decision

FAST Analysis: The project’s FAST diagram, shown in Figure 2.6, represents the functions that need be completed to reach the final design. On the left is the design goal, to design a device for tool condition monitoring. Reading the diagram from left to right demonstrates how these functions relate to one another. For example, the third stage of the diagram shows that data is collected by recording amplitude, filtering frequency bands, and

blocking noise. Alternatively, reading the diagram from right to left demonstrates why a particular component of the design is needed. For example, the third stage of the diagram shows that data is collected and information is transmitted in order to monitor the cutting tool. This results in a list of functions that must be completed in order to achieve the final design. The stages of the FAST diagram were used to determine the components that were used in the design.

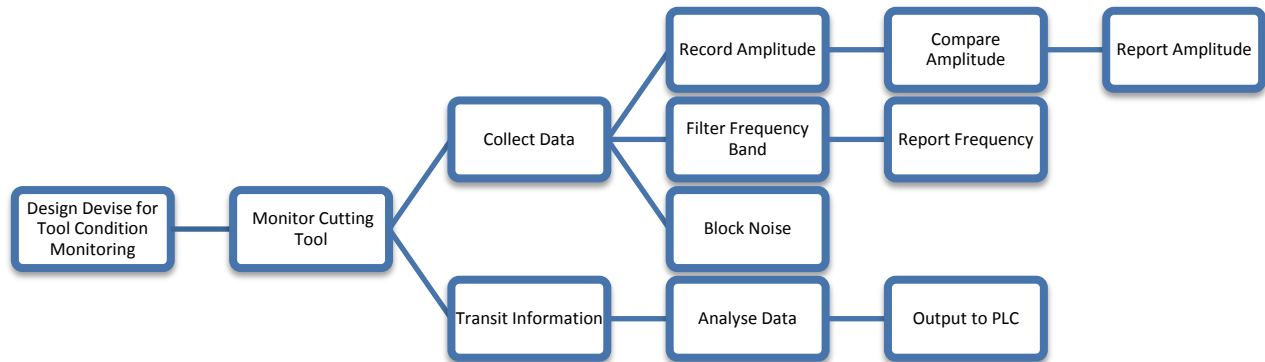


Figure 2.6: FAST Diagram

Analysis Circuit: To analyze the output of the accelerometer, the team designed a set of hardware to determine the frequency content and amplitude of the signal. Shown in Figure 2.7, this is done using an adjustable band pass filter, comparator, and a microcontroller. Based on the team's research, the frequency of the accelerometer's output should increase with tool wear. The adjustable band pass filter can be set to a specific frequency range relevant to tool life. This solution frequency analysis is both flexible and simple to implement.

Next, the comparator is used to compare the peak amplitude of the band pass filter to the output of an adjustable reference voltage. The positive terminal of the comparator is fed from the band pass filter output and the negative terminal from a filtered PWM output generated

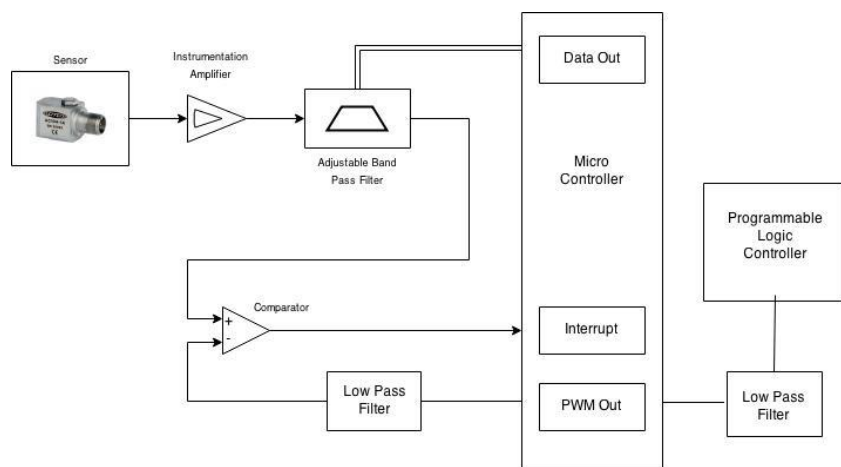


Figure 2.7: Circuit Block Diagram

from the microcontroller. If the amplitude of the filter output surpasses the reference voltage, the comparator output will be driven high, indicating that the magnitude of the signal at a set frequency has surpassed a reasonable level. Otherwise, the comparator output will remain low.

The output of the comparator drives an interrupt enabled pin on the microcontroller, indicating that a milestone in tool life has been reached. Within the interrupt service routine, the pass band of the filter and the PWM reference voltage can be adjusted to check for the next relevant condition and the output to the PLC can be adjusted to reflect the current level of wear.

Part Selection: The accelerometer chosen was made by Connection Technology Center, Inc.. The sensor has a rating of 100 mV/g, meaning that for each multiple of gravity acceleration it detects, it will output a voltage 100 mV above or below the signal ground. It can detect up to +/- 50g of acceleration.

The chosen design requires multiple band pass filters built for each frequency that is determined to indicate tool wear. However, this implementation is labor intensive, spatially inefficient, and inflexible. Instead, the team used a MAX262 chip, an adjustable band pass filter IC made by Maxim Integrated. This allowed the team to filter a wide range of frequencies using only one chip.

The MAX262 chip has switched capacitor filters whose cutoff frequency can be changed by software control. The MAX262 has the option to change both the cutoff frequency and filter quality for two on chip filter sections. The chip also provides high pass, low pass, band pass and notch filter outputs for each individually adjustable filter section based on the parameters provided by the microcontroller. The filter sections can be cascaded in order to provide sharper filtering. The MAX262 can have a cutoff frequency from 0 - 140 kHz and costs around \$15.

The microcontroller chosen was the MSP430. The MSP430 is a low power, inexpensive microcontroller manufactured by Texas Instruments. It has the advantages of being simple to program and interface with.

Critical Customer Specifications: The team believes that this design meets a great deal of the customer's specifications. As per the project description, this system design should be able to detect the wear on a single tool during machine operation. The hardware built to interface with

the sensor and analyze its output will be able to produce a 0 to 10 V signal based on the sensor output and be run off of a 24 V power supply. The system will also be capable of the necessary auto calibration; if it is reset after a tool is replaced, the system will begin checking for the first signs of tool wear again. The sensor is also robust enough to withstand the harsh environment within the lathe.

The specifications that weren't met were discussed and negotiated with the customer. For example, the project description stated that the sensor should be 2" x 2" x 2" and attached to a back wall of the machine, 4' from the lathe operation. This specification was given because the customer envisioned a solution using an acoustic microphone. After reviewing the team's research with the customer, it was determined that the dimensions and placement specified were negotiable in the circumstance of a promising alternative sensing method. Additionally, the 2" x 2" x 2" size requirement pertains to the size of the elements being placed within the lathe, and does not apply to external circuitry.

2.3 Schedule and Project Planning

One of the primary hurdles of this project was designing a system around data that would not be available until after the system was built to gather the data. One way the team chose to handle this, was to build a system that was flexible and could be adjusted based on the data gathered. By using an adjustable filter IC instead of a single filter or set of filters, it was simple to adjust the frequency band and amplitude based on what differences the team found indicated tool wear. Additionally, a state machine in the interrupt service routine allowed the team to check for specific conditions of interest rather than assuming that the sensor output would map directly to the output to the PLC.

Particularly given the time constraints of the semester, it was critical that the team built a system that could be adapted based on the data that was found to indicate differences between a good and bad tool. This significantly reduced the critical path for the project timeline; instead of waiting to have data to begin building a circuit around the sensor, a system could be built simultaneously and variables altered in software later based on the findings.

The project as a whole was divided into multiple work phases that identify the tasks required within the project. A Gantt chart with the various tasks and work phases was built to

visualize these tasks and assure the work progress is on time. The Gantt chart was developed at the early stages of the project where the final design details were unknown; hence, most of the tasks are in general terms. The Gantt chart can be found in Appendix 3.

The following are descriptions of the 5 phases of the project:

Phase 1: Initial Research Phase: This phase included the initial meetings with the customer and the development of the customer needs and constraints. This also introduced the team members to each other and assigned different roles for each member.

Phase 2: Design Development Phase: This phase included looking at possible design solutions and making decisions on parts on components for the design. This phase included meetings with different faculty of the MSU College of Engineering, Dr. Robert McGough and Dr. Thompson, for their consultancy on different design approaches. During this phase, the initial circuit design was developed and the sensor selection was made. All required parts were ordered. Finally this phase included the development of the Project Proposal to the customer with finalized device design selections.

Phase 3: Prototyping and Testing Phase: After all parts were ordered, this phase included building the circuits and systems for the prototype and testing individual systems separately. The sensor power-supply circuit was built which then allowed the sensor to be tested within the laboratory. This phase also included the development of the software for the controlling the band-pass filter and PWM outputs, which was also tested separately within the laboratory.

Phase 4: Final Design Building Phase: This phase was focused on compiling various hardware sections and debugging the project as a single unit. This allowed the team to then run different tests on the device at different machine shops at MSU and at the customer's shop. Lastly, the final components were housed within a presentable layout for the customer.

Phase 5: Conclusions Phase: This phase spanned the duration of the last week, and included working on the technical communications tasks including the final report, final presentation and demo, design day poster and the website.

2. 4 Project Budget

According to the ECE 480 course description, each team was granted a \$500 budget to complete their project. Great Lakes Control & Engineering also set a \$250 per unit cost on each sensing system developed. The final cost of the project is broken up into several categories in which specific components are itemized. They are namely the sensor, microcontroller, and analog circuitry. After completing research, it was determined that the bulk of the budget for this system should be invested in a high-quality, durable accelerometer. To the team's benefit, the unit selected only consumed a third of the total available budget. Also, by utilizing the ECE shop inventory, many hardware components could be obtained for free, thus resulting in an overall cost savings. A detailed breakdown of the budget is displayed below in Table 2.2.

Component	Quantity	Price	Subtotal
MSP430	1	\$0.00	\$0.00
PIC32 Pinguino Microcontroller	1	\$16.70	\$16.70
MAX262 Programmable Filter	4	\$16.48	\$66.58
CTC AC130 Accelerometer	1	\$150.00	\$150.00
Accelerometer shielded cable	1	\$57.50	\$57.50
Accelerometer mounting disk	1	\$6.50	\$6.50
20 pin SIL socket	4	\$1.89	\$7.56
Breadboard, resistors, capacitors, voltage regulator, wire	-	\$0.00	\$0.00
Shipping	-	\$13.52	\$13.52
Total			\$318.36

Table 2.2: Itemized Cost of all Components Used

Chapter 3: Technical Description

The hardware and software elements of the project overlap significantly and were developed in conjunction. While some elements, such as the power supplies, are strictly analog, others have both hardware and software components to their implementation, such as the MAX262 filter IC which processes an analog signal based on programmable parameters. For this reason, this section is structured around each of the primary project elements. Each of these sections describes both the hardware and software efforts needed to implement that element, the schematics of which can be found in Appendix 3.

The team chose the MSP430 to control the digital elements of our circuitry. The main functions of the MSP430 software were to program the MAX262 adjustable band pass filter IC, output two PWM signals for the comparator and the final output, and to trigger an interrupt that would reprogram the filter and PWMs based on the output of the comparator.

3. 1 Power Supplies

The device is powered from the lathe's Programmable Logic Controller with 24V. This needed to be stepped down to several other levels required by the circuitry. The voltages required are 19V, 5V, and 3.3V. The 19 V supply powers the sensor and most of the analog circuitry. This supply is created with an LM317 adjustable voltage regulator. The voltage output of the LM317 is a function of two resistors used to adjust the voltage. These were chosen to have an output of 19V. Fixed linear voltage regulators are used to create the 5V and 3.3V supplies. The supplies are cascaded to minimize dropout voltage across the regulators themselves. This configuration cuts down on the power dissipated as heat. The 5V supply is necessary for the adjustable band pass filter chip, while the 3.3V is used for the microcontroller. There are filter capacitors throughout the power supply to ensure clean supply rails.

3.2 Sensor Interface Circuit

The sensor requires a constant current power supply with a voltage of 18 – 30 V. The power supply circuit given in the application notes of the sensor, and shown in Figure 3.1, calls for a constant current diode with a current between 2 mA and 10 mA. Since constant current diodes as a discrete component are an obscure part, the team chose to implement one with a

JFET transistor and resistor. The value of the resistor was first calculated and simulated in PSPICE before being tested with the sensor.

3.3 PWM and DC Filters

There are two adjustable voltages required by the circuit. The first is the previously discussed adjustable level used to set a comparator threshold. The

other is the overall output of the system, the 0-10V signal used to communicate the remaining tool life with the lathe's Programmable Logic Controller.

These adjustable voltage levels are implemented by filtering two PWM outputs of the microcontroller. The low pass filters were implemented as second order active filters using op-amps in a modified non-inverting amplifier configuration. An LM324 quad op-amp is used to implement these filters.

The gain of each filter was determined by the desired output range of the voltage level. For the signal going to the comparator, a gain of 1.8 was chosen to allow for a voltage output range of 0 – 6V. This range overlaps well with the output of the filter IC, which is 5V. For the overall output PWM filter, a gain of 3 was chosen, yielding a range of approximately 0 – 9.9V. In general, the output voltage can be estimated using the formula:

$$V_{out} = 3.3 \times gain \times duty\ cycle$$

$$0 \leq duty\ cycle \leq 1$$

3.4 Comparator and Interrupt

A single op-amp in an LM339 quad op-amp chip is used in our circuit for the comparator. The comparator circuit is very simple, using only 3 resistors. A pull-up resistor is necessary for the LM339 to saturate. The other two resistors form a voltage divider to step the saturated output of 19V down to 3.3V, so it can interrupt the microcontroller without risk of damage to the chip.

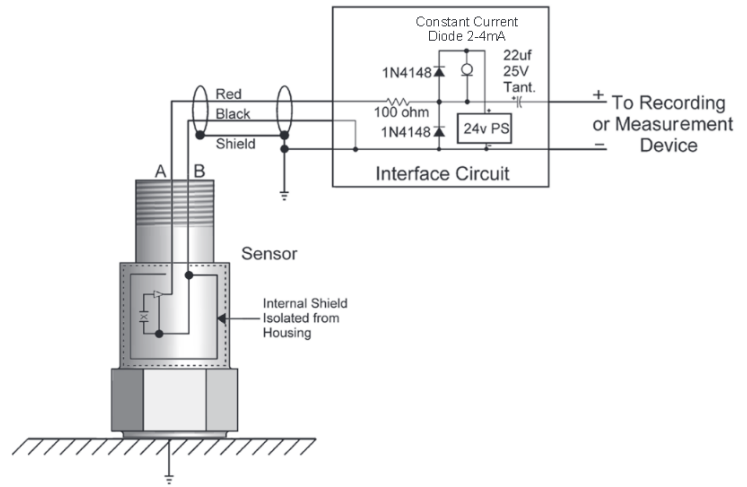


Figure 3.1: Sensor Interface Circuit

When the output of the comparator goes high, indicating that the amplitude of the filter output has surpassed the PWM reference voltage, the rising edge triggers an interrupt on the MSP430. In order to change the values of the PWM outputs and the frequency band of the filter during operation in response to increased tool wear, the team have implemented an interrupt service routine (ISR) to reprogram these values when the previous conditions for amplitude and frequency have been met.

Once inside the ISR, there is a state machine that can set the filter and PWM values to check for a new frequency and amplitude. Designing the system in this way allows us to program the system to check for particular conditions rather than mapping the output of the sensor directly onto the signal to the PLC.

3.5 Adjustable Band Pass Filter

The team opted to use the MAX262 programmable switched capacitor filter IC for this design. This chip offers a wide range of center frequencies and bandwidths selected under microprocessor control. The chip provides output for low pass, band pass, and high pass based on the parameters given. The center frequency is determined as a function of the external clock frequency and a selected pre-defined ratio based on the internal register value set in software.

The chip can be powered with a +/-5V supply, or a single ended +5V supply. The team opted to use a single 5V supply to avoid the need for negative voltages. In this configuration, the ground pin is biased at +2.5V, and the negative supply is grounded. Thus, any signal fed into the filter should have a DC offset of 2.5V, and the output of the filter has this same offset. There are some drawbacks to running the filter off of a single ended supply, including a large amount of error in the clock to center frequency ratios supplied in the datasheet. The datasheet does not supply

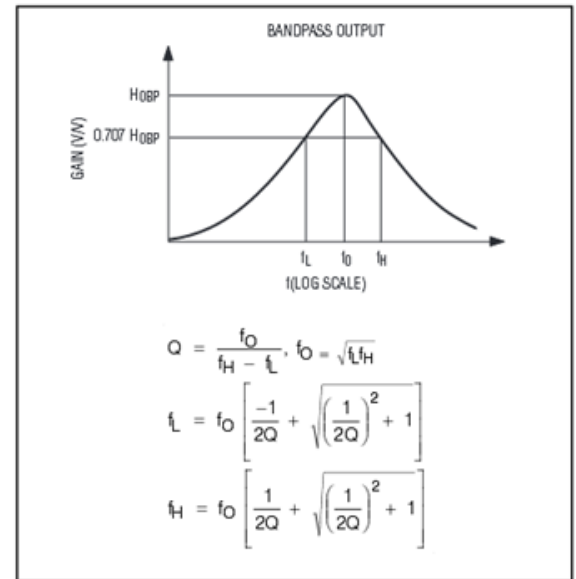


Figure 3.2: Filter Parameter Equations

much information on how the ratios change, and when running in this mode, trial and error is the best method of getting the desired filter parameters.

DATA BIT		ADDRESS				LOCATION
D0	D1	A3	A2	A1	A0	
FILTER A						
M0 _A	M1 _A	0	0	0	0	0
F0 _A	F1 _A	0	0	0	1	1
F2 _A	F3 _A	0	0	1	0	2
F4 _A	F5 _A	0	0	1	1	3
Q0 _A	Q1 _A	0	1	0	0	4
Q2 _A	Q3 _A	0	1	0	1	5
Q4 _A	Q5 _A	0	1	1	0	6
Q6 _A		0	1	1	1	7
FILTER B						
M0 _B	M1 _B	1	0	0	0	8
F0 _B	F1 _B	1	0	0	1	9
F2 _B	F3 _B	1	0	1	0	10
F4 _B	F5 _B	1	0	1	1	11
Q0 _B	Q1 _B	1	1	0	0	12
Q2 _B	Q3 _B	1	1	0	1	13
Q4 _B	Q5 _B	1	1	1	0	14
Q6 _B		1	1	1	1	15

Figure 3.3: Description of MAX262 Address Space and Storage

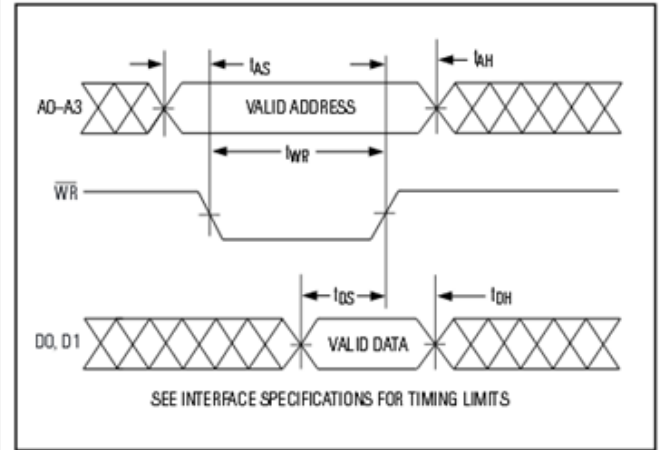


Figure 3.4: MAX262 Timing Diagram

The team chose to clock the MAX262 with a 1 MHz crystal oscillator. The crystal oscillator requires only a 5V power supply to output a 50% duty cycle square wave with great accuracy. A clock frequency of 1 MHz gives provides a center frequency range from around 7.2 kHz to 25.8 kHz. The team determined that this frequency range overlapped well with the data gathered from good and bad cutting tools.

To program the MAX262 chip, the correct data correlating to a specific center frequency and pass band must be determined, then the data must be sent to the chip through a series of write operations. The equations in Figure 3.2 show the basic method for calculating filter values. Once the desired output has been calculated, the correct data to be sent to the filter can be determined from the data sheet. The actual center frequency of the chip is a function of the input clock to the filter and so it must be calculated in conjunction with this value.

The MAX262 chip uses seven parallel inputs to receive data and set the center frequency and pass band for the two on chip filters. Of these seven pins, two are data inputs, four are address bits, and one is a write enable line. Figure 3.3 demonstrates the programming requirements for the chip. M0:M1 indicate the mode of operation, F0:F5 are the program code bits setting the center frequency, and Q0:Q6 set the pass band frequencies. This series of data must be sent two bits at a time to the specified addresses, therefore requiring a series of eight write operations to set a single filter. Figure 3.4 shows the timing diagram for these inputs. In code, all data and address bits are set, then the write enable line is brought low. After a small delay, the write enable is brought high again and the address and data bits can be reset.

3.6 Prototype Implementation

While testing the various circuits on a breadboard, it became apparent that a more robust solution would be required. The team found that moving to a soldered PCB produced more predictable results with the adjustable band pass filter circuit. The PCB prototype, shown in Figure 3.5, is completely self-contained, with the microcontroller on the board as well. However, this means that the microcontroller must be removed to be reprogrammed with new firmware during debugging.

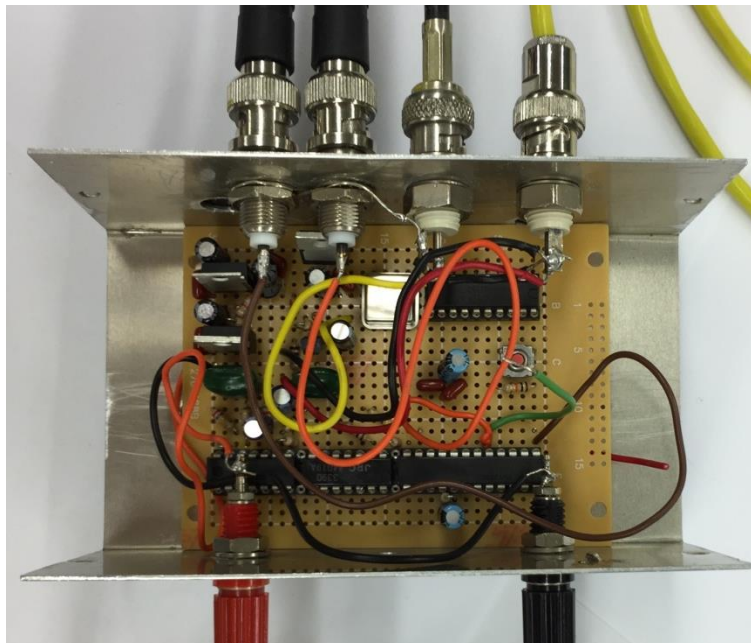


Figure 3.5: Hardware Prototype

Chapter 4: Testing and Validation

The testing plan for the project included multiple stages. First, the team had to test and tune the analysis circuit and the software for controlling the band-pass filter as well as testing and gathering data from the sensor. These two stages were developed and tested in parallel within the same time frame. Once these two systems were proven to function as expected, they were tuned to work together and tested at the machine shop.

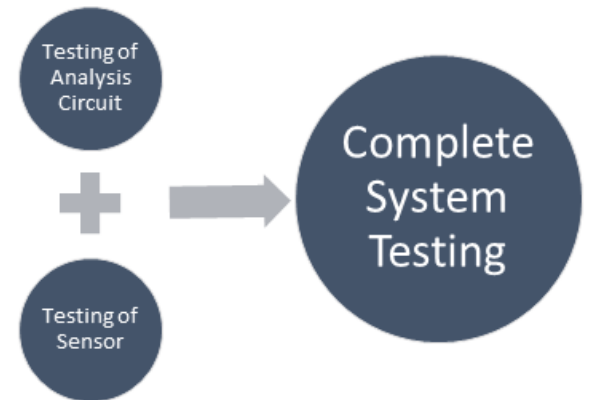


Figure 4.4: Project Testing Plan

4.1 Testing Plan and Data

Hardware: To test the analysis circuit, the team used a function generator to simulate the sensor output. The filter was programed to detect a frequency band of interest, as determined by the data collected. In this case, the center frequency of the pass band is 8.4 kHz. First to test the filter functionality, the function generator output was set to the center frequency and then to another frequency outside the pass band. In Figures 4.2 and 4.3, the function generator output is the top waveform in green and the frequency of the waves is shown in the measurements panel to be 8.4 and 7.4 kHz, respectively, while the amplitude of the wave is held constant at 300mV. The filter output is the middle waveform, which demonstrates the difference in output at these frequencies. The MAX262 chip has a significant gain associated with the filter output when the

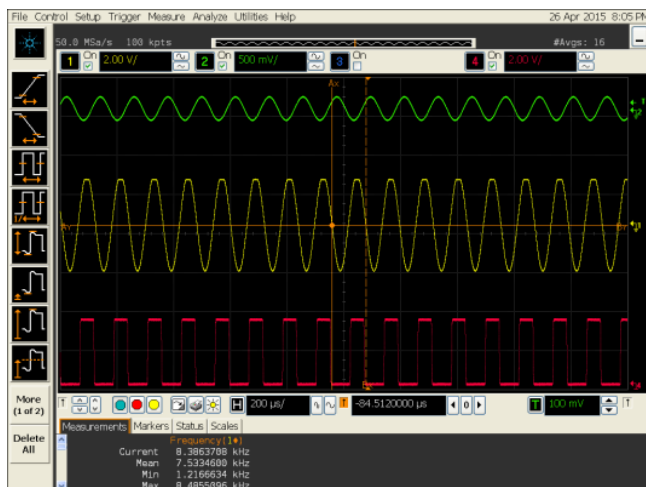


Figure 4.2: Output within Pass Band at 8.4 kHz

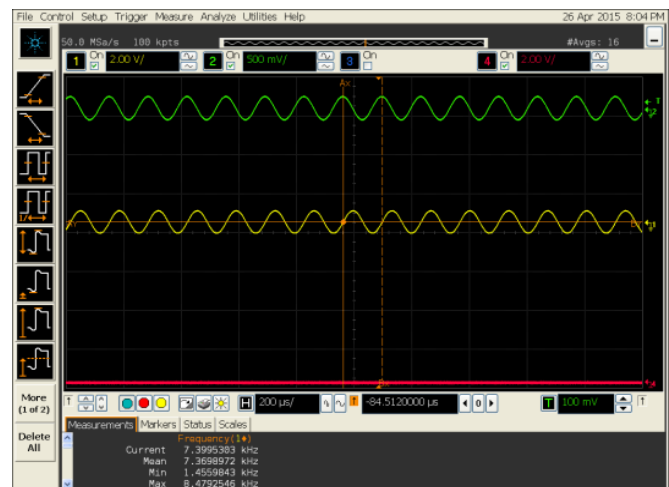


Figure 4.3: Output outside Pass Band at 7.4 kHz

input signal is within the pass band, as shown by the difference in amplitude of the filter output at the center frequency versus another frequency outside the pass band.

The next functionality tested was the comparator that checks the filter output against a reference voltage set by one of the filtered PWM outputs. When the peak amplitude of the filter output surpassed the reference voltage, the output of the comparator was pulled high. In Figures 4.2 and 4.3, the comparator output is the bottom waveform in red. In Figure 4.2, it is clear that the output is being pulled high when the amplitude of the waveform increases beyond this threshold, then returns to 0 V when this condition is no longer met. In comparison, in Figure 4.3, the function generator frequency is outside the pass band, the amplitude of the filter output is below the reference voltage, and the comparator output is never pulled high.

The interrupt service routine and the state machine inside were tested by setting a different PWM in each state and then triggering the interrupt by pulling the interrupt enabled pin on the MSP430 high. Each time the interrupt was triggered, the PWM duty cycle increased, demonstrating that on the rising edge, the MSP430 entered the ISR and was successfully moving through the state machine. Once this function was verified, the comparator output could be attached to the interrupt enabled pin.

Additionally, other nodes and individual components of these functions were tested and debugged throughout the process of building this system. For example, the MSP430's PWM outputs have amplitude of only 3.3 V, so the filters used to convert them to a DC wave also required amplification. This was necessary both to generate an appropriate reference voltage for comparison against the filter output and to generate the 0-10 V output to the PLC. Additionally, the comparator uses the 19 V supply rail, so a voltage divider was needed to produce a lower DC voltage appropriate for the MSP430. All of these nodes and interface elements were verified individually.

Sensor Circuit: As mentioned in Chapter 3, the sensor needs the accompanying power-supply circuit to function which was seen in Figure 3.1. This circuit was tested separately to ensure the sensor outputs consistent results. To measure the output from the sensor, the sensor signal was connected to the laboratory's digital oscilloscope to plot the voltage and Fast Fourier Transforms (FFT) signals. The sensor was tested over multiple stages.

First, the sensor was tested manually by rapidly moving the sensor by hand and observing the oscilloscope signals. This proved the functioning of the power-supply circuit and sensor.

Next, the sensor was tested on a manual drill press. This allowed the team to mount the sensor directly to an aluminum work-piece and manually introduce vibrations through the drilling of holes through the work piece. The drill-press introduced much higher frequencies than before and proved the sensor to work within the 0 to 20 kHz range. Figure 4.4 shows the set-up used while operating the drill press.



Figure 4.4: Testing Set-up Using Drill Press

1) Sensor placed inside work piece 2) Work piece 3) Drill Press

The sensor was then tested on a single-spindle semi-automatic metalworking lathe with a stock carbide cutting tip available at the MSU machine shop. This provided a very accurate simulation of the problem and helped the team gather preliminary data on what the sensor output might look like. The sensor was placed at different locations on the tool holder to identify the location with the greatest range of both output amplitude and frequency. As expected, the closer the sensor was mounted to the cutting operation, the better the sensor output was. Different tests were made for new cutting tools compared to worn out ones to study the differences. Figure 4.5 shows the set-up used for testing the sensor on the single-spindle lathe. While, Figure 4.6 shows the voltage (yellow) and FFT (white) readings on the oscilloscope for a bad tool cutting at 360rpm.

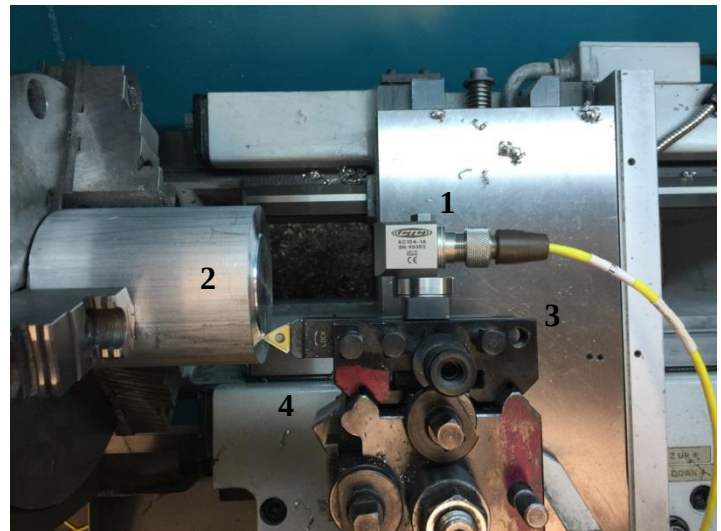


Figure 4.5: Testing Set-up Using Single-Spindle Lathe

1) Sensor mounted using magnet 2) Work piece 3) Cutting tool holder 4) Cutting tool tip

Afterwards, the sensor was tested on a single-spindle semi-automatic metalworking lathe with the required box tool available at the customer's machine shop. This allowed the capture of data with the cutting tool specified in the project description. The box tool can be seen in Figure 4.7.

Finally, after gathering data from the previous four testing stages, the team returned to the MSU machine shop and ran an extensive series of tests for a number of different conditions. The set-up of the final mounting is seen in Figure 4.8.

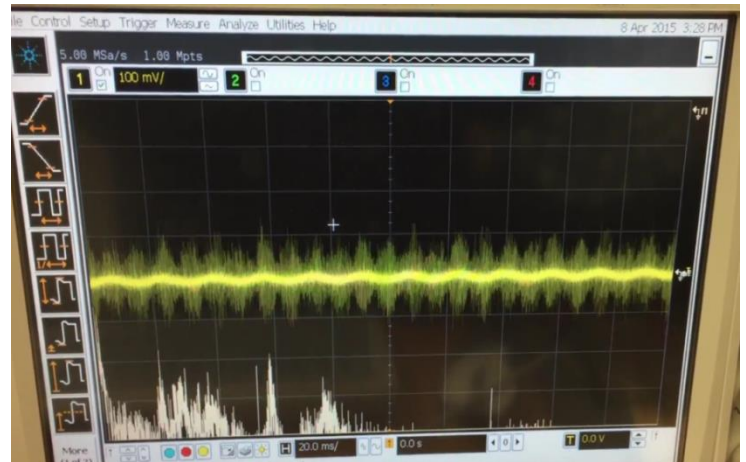


Figure 4.6: Voltage and FFT Readings from Lathe Testing



Figure 4.7: Box Tool in the Tool Holder



Figure 4.8: Machine Set-up for Final Testing Stage

At this point, the team decided to optimize the device for the single spindle lathe available at the machine shop with the stock cutting tool. Building a system that is functional for a specific machine requires multiple trips to gather data, test the device, and make adjustments. Given the time constraints of this project, the MSU machine shop provided the only accessible location for extensive testing. This eliminated the possibility of testing on a multi-spindle lathe machine because the MSU machine shop only has single-spindle lathes. Moreover, this also only allowed the team to use the stock cutting tip provided by the MSU machine shop rather than the 'box tool' required by the sponsor.

The team's goal regarding data collection then became 1) to make the system functional for the given machine and 2) to gather enough data to extrapolate what might happen in other circumstances. Due to the large amount of variables that could affect the results, it was decided to only focus on three different spindle speeds at a constant cutting tool feed-rate. It was also decided that measurements would be taken for a new tool vs a worn out tool. As a result, the data only indicated the difference between when the cutting tool was good (new) or bad (dull) and eliminated the possibility of mapping out tool life in a linear fashion.

This provided three data collection conditions for each good and bad tool. The speeds were selected to be 480-rpm, shown in Figure 4.9; 700-rpm, shown in Figure 4.10; 1000-rpm, shown in Figure 4.11. Five different samples were taken for each tool under each condition. This provided sufficient data to look for trends on the FFT plots to compare the good (cyan) vs bad (red) tool. The results of this final phase of testing were as following:

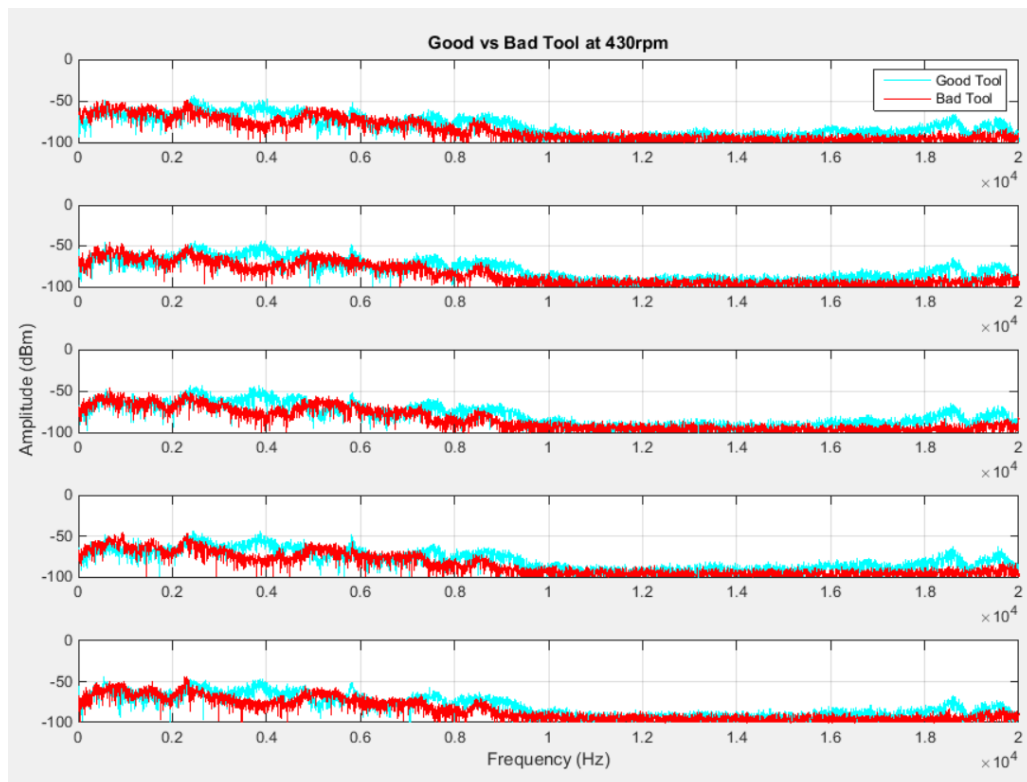


Figure 4.9: FFT of Good Tool vs. Bad Tool at 430rpm

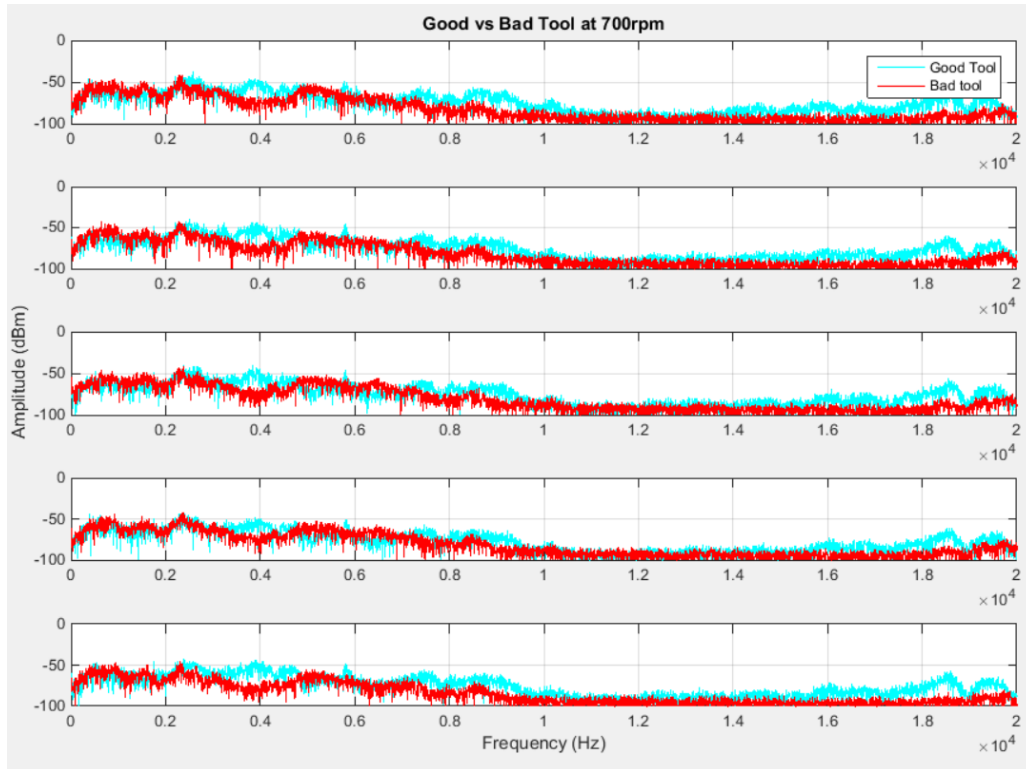


Figure 4.10: FFT of Good Tool vs. Bad Tool at 700rpm

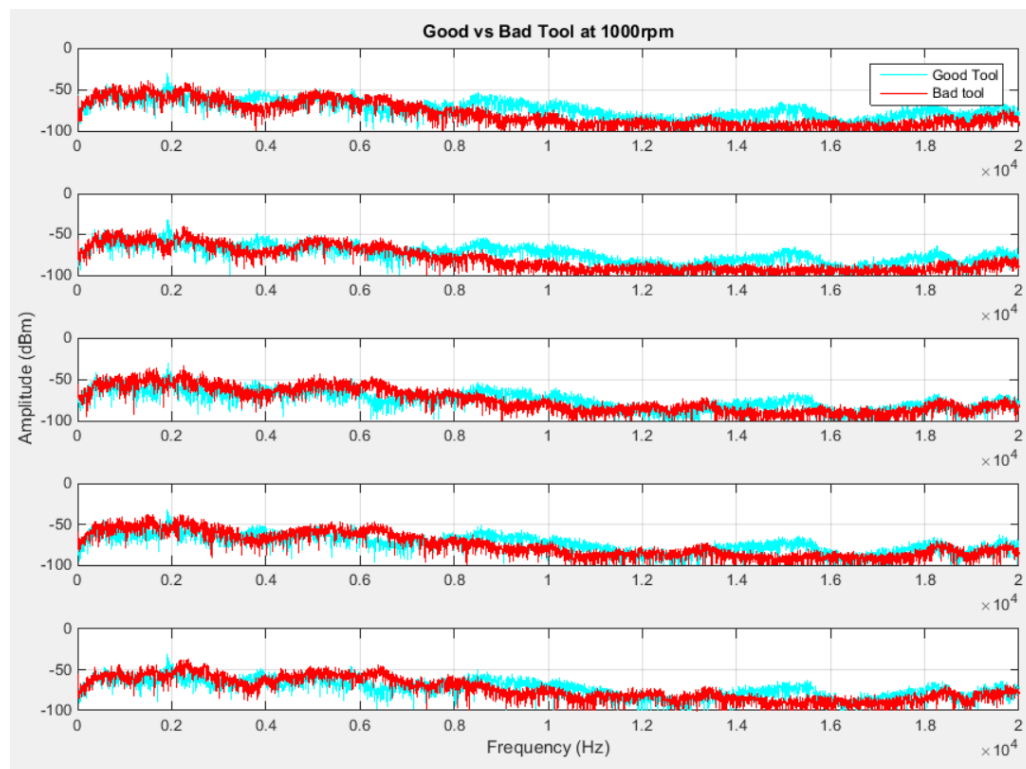


Figure 4.11: FFT of Good Tool vs. Bad Tool at 1000rpm

Form Figures 4.9 to 4.11, the following conclusions could be made:

- The bad (dull) tool has a dip in frequency components around 0.4×10^4 Hz (4 kHz) compared to the good (new) tool.
- All the frequency components of the good tool are larger than that of the bad tool within the 8 kHz to 10 kHz range.
- The amplitude of the FFT components of interest (2 kHz to 12 kHz) are all significantly small. These signals are only -100 to -50 dBm which is only about 2.25 μ V to 2.25 mV. A signal with such low amplitude would be significantly difficult to detect without significant amplification.

4.2 Final Outcomes

This project provided a platform for the team to build an initial design, upon which further development could be made. Within the time and budgets constraints of this project, the team developed a system to monitor tool condition on metalworking lathe machines. However, data limitations introduced a significant setback for the complete implementation of this system on the customer's six-spindle lathe machine. For these reasons, the team has opted to call the outcome of this project a proof of concept rather than a ready-to-install product.

Nonetheless, the team believes that the system could be reasonably adapted to the customer's specifications. With the results seen in the previous section, it was proven that dull tools produce lower amplitudes at certain frequencies than new tools. The FFT amplitude dips at approx. 4 kHz and in the 8 to 10 kHz range, which indicates this trend. These amplitude dips were seen across all spindle speeds, which proves that this conclusion could be generalized to high-speed operating machines, as is the customer's case. These frequency dips' locations will likely differ for different cutting operations such as using the box tool. However, the device could be easily adjusted by controlling the band-pass filter to check for different frequency ranges. Given the flexibility of the system developed, modifications like these could be easily implemented for the device to work on different machines.

The other conclusion made from the data in the previous section was that the amplitude of the sensor output is very low voltage. The output range for the signals of interest between 2 kHz and 12 kHz is only -100 to -50dbm which converts to 2.25 μ to 2.25mV. With such low

amplitudes, the analysis circuit would be incapable of distinguishing between sensor signals. Moreover, the circuit components' noise would decrease the signal-to-noise ratio (SNR) even more. A possible solution could be to purchase one of the higher sensitivity sensors mentioned in Chapter 2. Most of these sensors also have built-in preamplifiers to amplify the sensor outputs and can be purchased with an accompanying amplifying circuit that can increase the SNR of the sensor at different frequencies. These sensors and pre-amplifier circuits were too expensive to lie within the budget allocated for this project.

Nonetheless, the analysis circuit and algorithm developed for evaluating the sensor signals are still compatible with any sensor if minor modifications are made. This circuit and algorithm are the core of the team's development efforts. The team believes that linking the successful circuitry and algorithm with the results of the data plotted from the sensor would make for a complete system.

All the circuits and components of this project were finally housed within a metallic project box to protect all components inside. Figure 4.12 shows a picture of the project box along with the connected sensor module.



Figure 4.12: Sensor and Project Box

Chapter 5: Final Cost, Schedule, Summary, and Conclusions

Team 10 succeeded in using a sensor to detect discernible differences in tool wear and in designing and building a device that is capable of monitoring the amplitude and frequency of a waveform, and setting a 0 to 10 V output based on this data. However, due to time constraints, it was not possible for the team to do extensive testing needed on the multi-spindle late described in the project description. Team 10 believes that significant progress has been made in terms of quantifying tool condition through data collection and analysis. Both the data analysis techniques and the device built could be adapted in the future to other machines.

If the team were to continue with this project, there are many future avenues to explore. The largest hurdle currently is the small signal amplitude and the poor signal to noise ratio at the frequencies of interest coming from the accelerometer. The best option would likely be a combination of investing in a higher resolution accelerometer, perhaps 500 mV/g or 1 V/g, and designing a low noise differential amplifier to pick up the signal. Amplifying such small signals can be very tricky to do without also amplifying noise, burying the signal within it. Amplifiers for tool monitoring applications are available as part of complete tool monitoring systems or available to purchase with individual sensors. The high cost of such devices made this option infeasible for this project. Once another method of amplifying the signal is devised, it could easily be integrated with the infrastructure already built to determine amplitude of particular frequency components of the signal.

While other methods of sensing could certainly be explored further, the feasibility of using an accelerometer for this type of tool monitoring hasn't been completely ruled out. The benefit of the accelerometer is the low cost compared to the many application specific sensors for this purpose currently on the market.

Upon solving the amplification issue, data must be taken on the machine the device is to be applied to. Data should be taken at many points during the life span of one particular cutting tool. With this data, milestones in tool wear will be identified and our algorithm could be finely tuned to be able to pick them up. When milestones are hit, the device will update the Programmable Logic Controller on the status of the cutting tool.

The final cost of the device would be around \$300. This cost differs slightly from the project budget outlined earlier due to developmental costs. Moreover, many parts were obtained for free from the ECE Shop so the actual production cost would be slightly higher.

Appendix 1: Technical Roles

Ali ElSeddik - Manager



Ali's role in this project started with gathering research and looking into the background of tool monitoring systems and tool wear. He compiled an initial list of research papers and articles that later became a resource for the team to learn more about the applications of tool monitoring systems. Along with the team members, Ali proposed a variety of approaches to solving the problem and at the end it was finally decided that force sensing was the most suitable.

From there, the task was to research companies and suppliers for the sensor component of the device. This was an extensive and time-consuming stage of the project that caused later delays to the team. Ali was the primary contact person for the team in communicating with the companies for the purchase of the sensor. By summarizing and writing reports back to the team, it was decided that the best solution was to purchase an accelerometer that was cheaper than the force sensors and fitted within the project budget.

Finally, Ali helped set up the testing procedures and system validation after the prototype was built. He coordinated visits to the MSU engineering machine shop and communicated with the team sponsor for tests at the sponsor's facilities. He later worked on analyzing the collected data by writing MATLAB scripts and drawing conclusions from the trends seen while testing. The outcome of these tests approved the design of the circuitry that was built by the other team members.

Richard Skrbina - Lab Coordinator



Richard's technical role in the project was heavily focused on the development and design of the hardware. Beginning with the initial system block diagram, his focus was put researching methods and creating hardware capable of detecting frequency and amplitude of the accelerometer output.

A considerable amount of his time was spent researching what components are available on the market and deciding which ones to integrate into the design. When choosing the more simple components such as op-amps or voltage regulators, we opted to use ones that we had been already familiar with from other courses. The key component to determine frequency spectra however was very unfamiliar. There are many methods of determining the frequency content of a signal, including Fast Fourier Transform algorithms, Digital Signal Processors, and Digital Filtering. When he discovered that programmable switched capacitor filter chips were available, we opted to use one in place of the other software intensive digital filtering techniques. These chips can change their filter parameters based on micro controller input.

Once parts were selected and ordered, building prototype hardware became his priority. Richard scoured datasheets and other technical documents for information on how apply the chips to our Tool Monitoring System. Hardware development was done in a modular fashion. Small pieces of the circuit were built and tested on a breadboard before integrating them with the rest of the system.

Richard also spent a large portion of time building our prototype on a soldered perf-board. This final prototype is much more robust than the breadboard circuits built as a proof of concept. The perf-board prototype is entirely self contained, not relying on any external hardware to function.

During hardware development, Richard worked very closely with the team's software guru, Caitlin to get the system up and running. Long hours were spent in the lab getting the hardware and software to run as expected. There were also many team discussions when data collection was taking place on how our hardware would be able to make sense of the data it was collecting.

Kyle Burgess - Webmaster



Kyle's technical role was split between testing, research, hardware and software. In the early stages of the design process, Kyle researched different methods of sensing and frequency analysis with the team; he focused specifically on using an Accelerometer and Fast Fourier Transform to gather and process data. Fast Fourier Transform was later dropped for an Integrated Circuit with an adjustable band-pass filter, but an accelerometer was used in the final design.

The sensor arrived with documentation, and a schematic for the analog circuit needed for its operation. Kyle designed and wired the Constant Current Diode needed for the sensor circuit. He then modeled it in PSPICE and worked with part of the team to initially test the sensor; the oscilloscope was used to read frequency data from the sensor, which was mounted on an aluminum beam that was being drilled.

The adjustable band-pass filter IC had limited documentation, so testing had to be done. Kyle programmed the MSP430 clock to drive the IC at 1 MHz. The function generator was used to test the center frequencies of the adjusted band pass filter. He also rewired the IC power rails to be more stable. After initial testing, the MSP430 clock was replaced with a 555 Timer.

Kyle helped gather data for good and bad tools. The sensor was tested on a lathe that was provided by the sponsor, and on a lathe available at the ME machine shop at MSU. The sensor was mounted under the tool, which was decided to be the optimal location from prior testing. The lathe was run with different speed and feed-rate combinations for both new and dull tools. The oscilloscope data was captured using live screen-capture video, and data points were extracted into a MATLAB file.

Additionally, Kyle helped map the pins on the Pinguino Microcontroller that was originally ordered. However, the Pinguino Board was later scrapped due to poor documentation, and the MSP430 was used instead.

Caitlin Slicker – Document Preparation



In the early stages of the project, Caitlin spent a significant amount of time researching audio sensing methods. After the project design had been finalized, Caitlin's primary role on the team was software implementation and debugging in conjunction with the hardware development. This coordination was important due to the significant overlap between hardware and software systems in the project.

Caitlin wrote all MSP430 code and implemented each functionality in a modular fashion so it was accessible and easy to use for other team members. For example, the code to program the MAX262 filter chip requires eight successive, 7-bit parallel write operations. However, it can be implemented by the user with a function that takes parameters directly from the data sheet. Within the function, these parameters are parsed and converted to the correct binary values to be sent to the chip. This level of abstraction is important for quick prototyping and debugging of embedded systems.

Overall, the code written by Caitlin achieves the following functionality: 1) programs the MAX262 filter IC, 2) produces two PWM outputs, 3) configures a GPIO as a rising edge triggered interrupt enabled pin, 4) handles events through the use of an interrupt service routine (ISR), and 5) implements a state machine within the ISR to modulate the PWM outputs and the filter parameters.

Caitlin also assisted significantly in hardware prototyping and debugging. A significant amount of time was spent coordinated with Richard's hardware efforts to debug the filter and other embedded components. Ultimately installing the 1MHz crystal oscillator and validating the center frequency and cutoffs of the filters was a part of this process.

Caitlin assisted the test and data gathering portions of the project by evaluating methods of data capture using the software tool BenchVue, which interfaces with Agilent oscilloscopes and other hardware. She also played a significant role in the photographic documentation of the testing procedures.

Chris Vogler – Presentation Preparation



Chris's technical role was heavily focused on the research of sensors to provide data regarding the tool life of the six-spindle screw machine. Specifically, he investigated further into acoustic emissions technology and advised directing efforts shift to vibrational based methods instead of purely audio solutions. Once the decision had ultimately been made to use an accelerometer, Chris contributed to the research of general purpose units that would satisfy the requirements of the project. This process involved making contact with manufacturer representatives and obtaining quotes so that budget planning could occur.

After hardware and software development, design, and initial testing occurred, his priority shifted to real-world testing applications. The major decision was made to accomplish testing at the engineering machine shop in the basement of the Engineering Building, with trained professional staff present willing to extend their help in running tests (controlling speed, feed rate, safety procedures). He proposed further tests be run locally at MSU to save time and focus efforts on obtaining quick data while ensuring the consistency and accuracy of these tests.

Chris worked with Ali to conduct several data acquisition sessions at the engineering machine shop. This consisted of the setting up and configuration of testing equipment including the lathe, oscilloscope, power supply, and accelerometer. Data capturing and exporting methods were explored with the oscilloscope especially using math functions to include the Fast Fourier Transform (FFT) frequency analysis data. This data was then plotted for good and bad tools for several lathe speeds and analyzed. By coming to a consensus first with Ali and finally the remaining team members, Chris proposed solutions on how to interpret the data and apply the necessary procedures to ensure the circuitry and software was validated. This consisted of the identification of frequencies and consistent trends for output data.

Appendix 2: Literature Review

- [1] "Metal Cutting Training: Intro to Screw Machining 160," ToolingU, [Online]. Available: <http://www.toolingu.com/class-200160-intro-to-screw-machining-160.html>. [Accessed 29 April 2015].
- [2] Nordmann, "Effective Power and Torque," Nordmann Tool Monitoring and Process Control, [Online]. Available: <http://www.toolmonitoring.com/wirkleistung.html>. [Accessed 29 April 2015].
- [3] M. Groover, *Fundamentals of Modern Manufacturing: Materials, Processes, and Systems* 4th Edition, John Wiley & Sons, Inc., 2010.
- [4] V. Cook, "Acoustic Monitoring of Machine Tool Health Using Transmitted Sound," in *International Conference on Industrial Engineering and Operations Management*, Istanbul, 2012.
- [5] "Polar Patterns," [Online]. Available: eu.audio-technica.com/en/support/tutorials/. [Accessed 6 February 2015].
- [6] H. Robjohns and P. White, "Q: How do Shotgun Mics Work?," 1 December 2013. [Online]. Available: <http://www.soundonsound.com/sos/dec13/articles/qanda-1213-01.htm>. [Accessed 6 February 2015].
- [7] S. Kagami, Y. Tamai, H. Mizoguchi and T. Kanade, "Microphone Array for 2D Sound Localization and Capture," in *IEEE International Conference on Robotics and Automation*, 2004.
- [8] B. Van Veen and K. Buckley, "Beamforming: A Versatile Approach to Spatial Filtering," *IEEE ASSP Magazine*, pp. 4-24, 1988.
- [9] "Basic Principles of Vibrometry," [Online]. Available: <http://www.polytec.com/us/solutions/vibration-measurement/basic-principles-of-vibrometry/>. [Accessed 6 February 2015].
- [10] "American Society for Testing and Materials: Acoustic Emission," in *ASTM International*, Bal Harbor, 1971.
- [11] "Acoustic Emission Technology," [Online]. Available: <http://www.mistrasgroup.com/products/technologies/acousticemission.aspx>. [Accessed 21 February 2015].

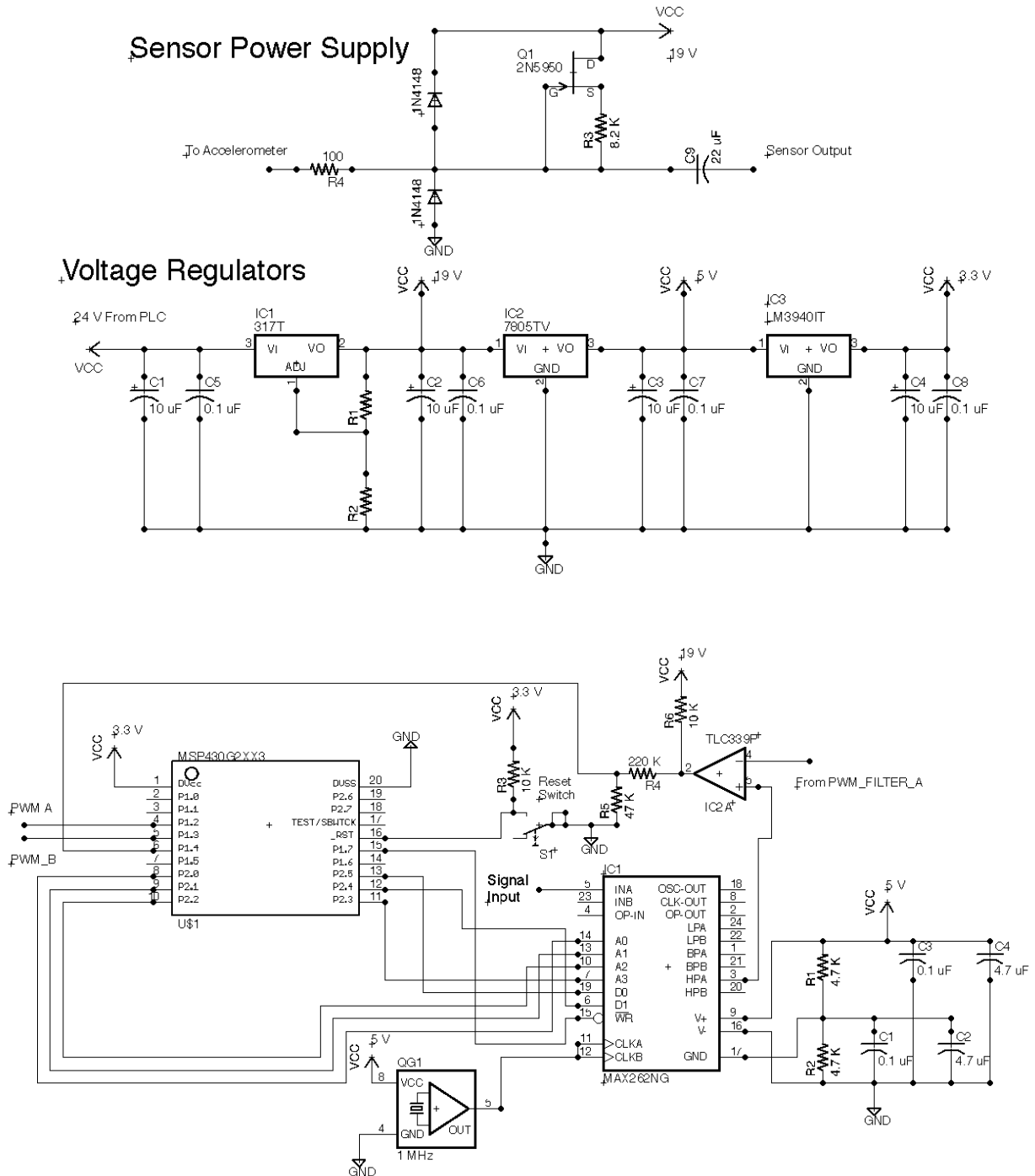
- [12] A. Trail, "Reliable Monitoring for Small Tools," 6 May 2006. [Online]. Available: from <http://www.productionmachining.com/articles/reliable-monitoring-for-small-tools>. [Accessed 6 February 2015].
- [13] *Hall Effect*, Encyclopædia Britannica Online., 2015.
- [14] "A Beginner's Guide to Accelerometers," DimensionEngineering: Robotics, Radio Control, Power Electronics, [Online]. Available: <http://www.dimensionengineering.com/info/accelerometers>. [Accessed 29 April 2015].
- [15] "Circuit Ideas for Designers: Band-pass Network," 1 January 2005. [Online]. Available: http://www.aldinc.com/pdf/wf_47002.0.pdf. [Accessed 6 February 2015].
- [16] "Acoustic and Vibration," [Online]. Available: <http://www.toolmonitoring.com/schall.html>. [Accessed 21 February 2015].
- [17] "Possible Sensor Positions for Tool Monitoring in Multi-Spindle Automatic Lathes," [Online]. Available: <http://www.toolmonitoring.com/mehrspindeldrehautomaten.html>. [Accessed 21 February 2015].
- [18] "Monitor Strategy of the Tool Monitor," 6 February 2015. [Online]. Available: <http://www.toolmonitoring.com/strategien.html>.
- [19] "Force," [Online]. Available: <http://www.toolmonitoring.com/kraft.html>. [Accessed 21 February 2015].
- [20] P. R. Aguiar, C. H. Martins, M. Marchi and E. C. Bianchi, Digital Signal Processing for Acoustic Emission, Data Acquisition Applications, 2012.
- [21] J. Keraita, H. Oyango and G. Misoi, "Lathe Stability Charts Via. Acoustic Emission Monitoring," *African Journal of Science and Technology*, vol. 2, no. 2, pp. 81-93, 2001.
- [22] Nordmann, "Force Sensor: BDA-Kralle," Nordmann Tool Monitoring and Process Control, [Online]. Available: http://www.toolmonitoring.com/pdf/sensoren/BDA-Kralle_Eng.pdf. [Accessed 29 April 2015].

Datasheets Accessed:

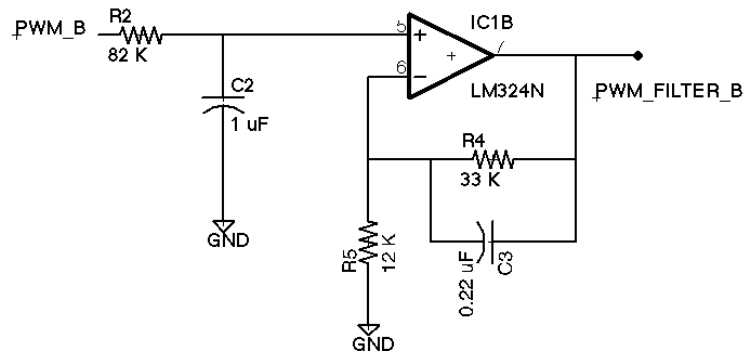
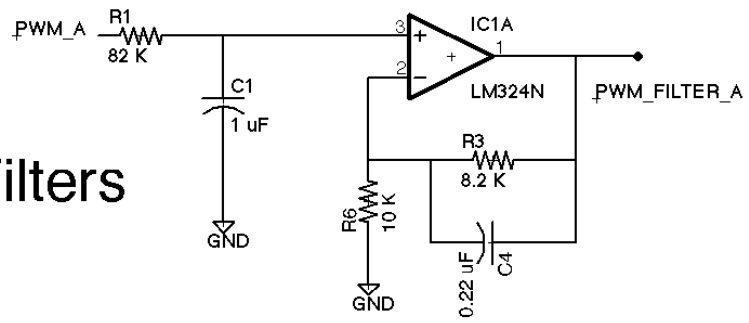
- MSP430G2553 - Micro controller: <http://www.ti.com/lit/ds/symlink/msp430g2553.pdf>
- MAX262 - Adjustable Switched Capacitor Filter:
<http://datasheets.maximintegrated.com/en/ds/MAX260-MAX262.pdf>
- LM 324 - Quad Operational Amplifier: <http://www.ti.com/lit/ds/symlink/lm224-n.pdf>
- LM 339 - Quad Comparator: <http://www.ti.com/lit/ds/symlink/lm339-n.pdf>
- LM 317 - Adjustable Linear Voltage Regulator:
<http://www.ti.com/lit/ds/symlink/lm117.pdf>
- LM 7805 - 5 V Linear Regulator:
<https://www.fairchildsemi.com/datasheets/LM/LM7805.pdf>
- LM 3940 - 3.3 V Linear Regulator: <http://www.ti.com/lit/ds/symlink/lm3940.pdf>
- 1 MHZ Crystal Oscillator: <http://www.jameco.com/Jameco/Products/ProdDS/354853.pdf>
- Accelerometer Application Note:
https://www.ctconline.com/FileUp/PrdDS2011/5_TI_PwrRequirements_DS.pdf

Appendix 3: Detailed Technical Attachments

Circuit Schematics:



PWM Filters



Gantt Chart:

